SEDIMENT CHARACTERIZATION IN THE INTERTIDAL ZONE OF THE BOURGNEUF BAY (FRANCE) USING THE AUTOMATED MODIFIED GAUSSIAN MODEL (AMGM)

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KEY WORDS: AMGM, Spectral Derivative Analysis, Moisture content, Particle size,

ABSTRACT:

Understanding of the uppermost layer of cohesive sediment beds provides important clues for predicting future sediment behaviours. Sediment consolidation, grain size, water content and biological slimes (EPS: extracellular polymeric substances) were found to be significant factors influencing resistance to erosion. The surface spectral signatures of mudflat sediments reflect such bio-geophysical parameters. The overall shape of the spectrum, also called a continuum, is a function of grain size and moisture content. Finally, composition translates into specific absorption features. Bourgneuf Bay site, south of the Loire river estuary, France, was chosen to represent a range of physical and biological influences on sediment erodability. This paper deals with the evaluation of a methodological approach, the Automated Modified Gaussian Model (AMGM), to extract from spectra the bio-geophysical properties on mudflat sediments. We have developed an automatic procedure based on the Modified Gaussian Model that uses, as a first step, the Spectroscopic Derivative Analysis (SDA). This AMGM algorithm is a powerful tool to deconvolve spectra into two components, Gaussian curves for the absorptions bands, and a straight line in the wavenumber range for the continuum. We focus our analysis on moisture content and grain size. Results show a quantitative relationship between moisture content and the way in which the shape of the molecular water band depth changes. With further analysis, we obtained an acceptable correlation between the moisture content, grain size and the AMGM continuum parameters. The relationship between grain size and moisture content, and the AMGM Gaussian and continuum parameters allows one to identify and separate the various types of water present in sediment (saturated water, free water, adsorbed water and hygroscopic water).

1. INTRODUCTION

The objective of our study is to map physical parameters influencing sediment dynamics in the intertidal zone of Bourgneuf Bay, SW France. Sediment erosion results from hydrodynamic forcing (wave and currents) on the flats as well as the erodability of the sediment. The main parameters influencing sediment cohesiveness / erodability are grain size, moisture content, mineralogy, and the biological components (microalgae, macrophytes, macrofauna, bioturbation). Abiotic and biological parameters translate into the spectral signatures of sediments in various ways:

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- mineralogy into specific absorption features depending on composition,
- grain size into the general shape or continuum due to scattering of light,
- moisture content influences the general shape, mainly in the infrared region, but also the strength of the liquid water absorption features,
- Chlorophyll-a concentration derived from the strength of the 675 nm absorption, is a reliable index for benthic microalgae biomass, but also sheds light over a complex pool of pigments and their degraded forms.

Our work relies on the Modified Gaussian Model (MGM, Sunshine & al., 1990). We describe here new approaches that consist in automating the procedure, the Automated Modified Gaussian Model (AMGM), and we present the results from the comparison of both techniques applied to a DAIS and a ROSIS image over Bourgneuf bay. Based on regressions defined from laboratory measurements, we then present maps of water content distribution resulting from regression-based AMGM algorithm.

2. DATA DESCRIPTION AND METHODOLOGY

2.1 Study site

The study area, previously studied by Combe et al., (2005), is located south of the Loire estuary (46-47°N, 1-2°W), in France. Our study focuses on Bourgneuf Bay, covered by the **D**igital **A**irborne **I**maging **S**pectrometer 7915 (DAIS 7915) and the **R**eflective **O**ptics **S**ystem **I**maging **S**pectrometer (ROSIS) hyperspectral images.

2.2 Dataset

Hyperspectral DAIS and ROSIS images were simultaneously acquired over Bourgneuf Bay in August 2002, in the framework of the HySens Campaign. ROSIS has 115 channels in the VIS range [430-870 nm], with a spectral resolution of 4 nm and a spatial resolution of 2 m. DAIS has 32 channels covering the VNIR range [400-1035 nm], with a spectral resolution of 15-20 nm and a pixel size of 5 m. Both data sets were converted to surface reflectance by DLR using the ATCOR 4 algorithm (Richter, 1996). Additionally, field spectral measurements and samples of sediments with and without biofilm were collected during various field campaigns. An ASD FieldSpec 3 FR$^{®}$ spectroradiometer was used to produce soil reflectance spectra in the 350-2500 nm wavelength range.

2.3 The Automated Modified Gaussian Model (AMGM)

Assessing bio-physical parameters requires extraction of spectroscopic information based on physical process modeling. The MGM developed by Sunshine & al. (1990) is considered as one of the most efficient analytical tools for deconvolving a reflectance spectrum and evaluate parameters that have a physical meaning. This algorithm decomposes the spectrum into a sum of modified Gaussian curves and a continuum in the energy space. However, more robust and stable automated method is desirable for large datasets like hyperspectral images. The core of our methodology is the development of the Automated Modified Gaussian Model (AMGM) process (see Verpoorter & al., 2007 for details).

3. RESULTS AND DISCUSSION

3.1 Deconvolution results

We test here the AMGM procedure on DAIS and ROSIS datasets. As shown on Figure 1, each pixel of the images is very well deconvolved, providing a good surface identification without *a priori* information. The method has the serious advantage to be fast and reproducible. Figure 1 shows the different constituents (*e.g.* Fucus, macro-vegetation, microphytobenthos, mud sand, moisture) observable in Bourgneuf bay. There is a good match between the modelled spectral (pink cross line) and the original spectra (black line) with negligible RMS residual errors both for DAIS with 0.0038 (Stdev 0.005) and for ROSIS with 0.0030 (Stdev 0.01).

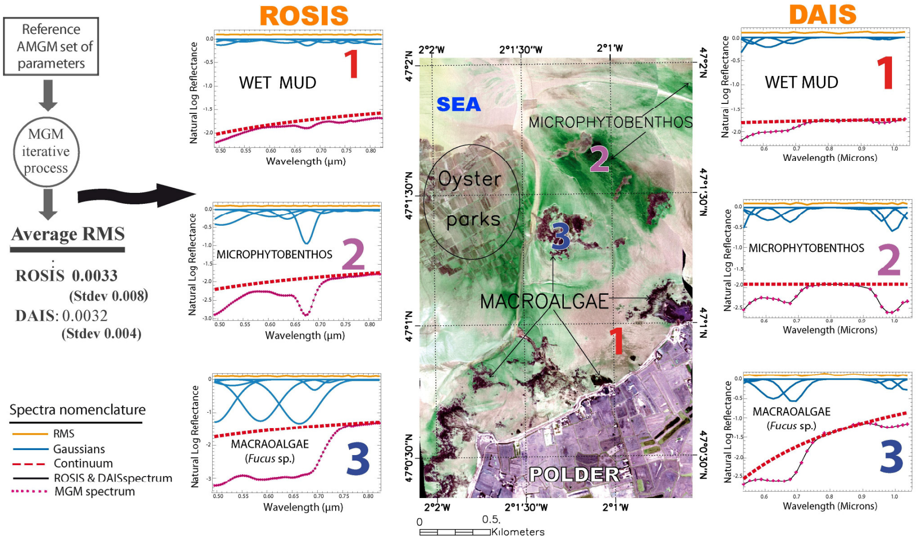


Figure 1. ROSIS and DAIS spectra (wet mud, microphytobenthos, macroalgae) fitted by a AMGM model. Deconvolution results (continuum and Gaussian parameters) allow us to give informations about the composition of topsoil of the mudflats for each pixel of the images dataset

3.2 Moisture content

3.2.1. Water absorption band analysis

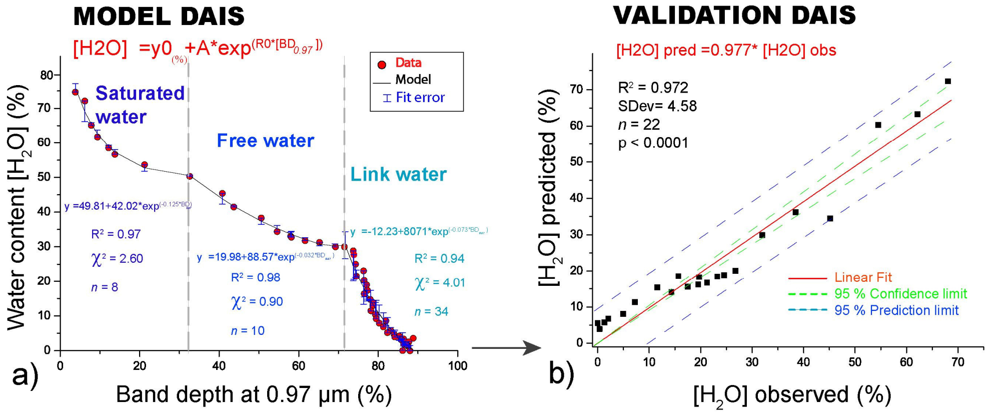


Figure 2. a) Exponential models to estimate water content after AMGM process at DAIS spectral resolution. X-axis is the measured water content in the sample, Y-axis is the estimation of the strength of the specific liquid water at 0.97 µm for a sand sediment sample. It became possible to separate 3 water-forms according to Beer-Lambert law: (1) saturated water; (2) free water; (3) adsorbed water. *n* = number of measurements used in the regression. b) Comparison between water content measured in the sample and water derived from inverting the equations derived from the training data set

Basically, moisture decreases the reflectance of sediments and affects the shape of the spectra due to the occurrence of well-defined water absorption bands. Most previous investigations have estimated moisture content based on hydration absorption bands overtones at 0.97; 1.20; 1.40; 1.90 µm (Ben-Dor & al. 1999; Liu & al. 2002). However some of these bands cannot be used with images because they are corrupted by atmospheric water vapour. Therefore we chose to focus on the 0.97 µm band which is less corrupted. The effect of soil moisture on reflectance was estimated for each sample by determining from laboratory spectral measurements the strength of the specific liquid water absorption at 0.97 µm as well as continuum variations from saturation to oven-dried. The Gaussian parameters (*i.e.* strength at 0.97 µm) was regressed against the gravimetric water content. Reflectance responses to moisture variations are non-linear and can be described by an exponential model according to the modified Beer-Lambert law (Figure 2-a). Three different sections can be identified in the regression curve that can be correlated to different hydration states: saturated water, free water filling macro- and micropores in the sediment and finally adsorbed water molecules loosely bound to particles. We therefore used three different models corresponding to the three hydration states. All three models showed high r^2 (0.98; 0.97; 0.94 respectively). Validation performed on test data sets also showed a strong r^2 of 0.972 and a slope close to one (Figure 2-b).

3.2.2. Continuum analysis

As mentioned above, moisture content also influences the general shape of the spectrum, also called the continuum. The continuum can therefore be considered as a possible proxy for moisture content excluding the hydrations bands. We have developed a simple model based on empirical relationships between moisture content and one of the parameters characterizing the continuum, the intercept, which translates the fact that the overall reflectance declines with increasing water content (Figure 3). Preliminary results indicate that the method is acceptable (r^2>0.91) when applied to laboratory spectra.

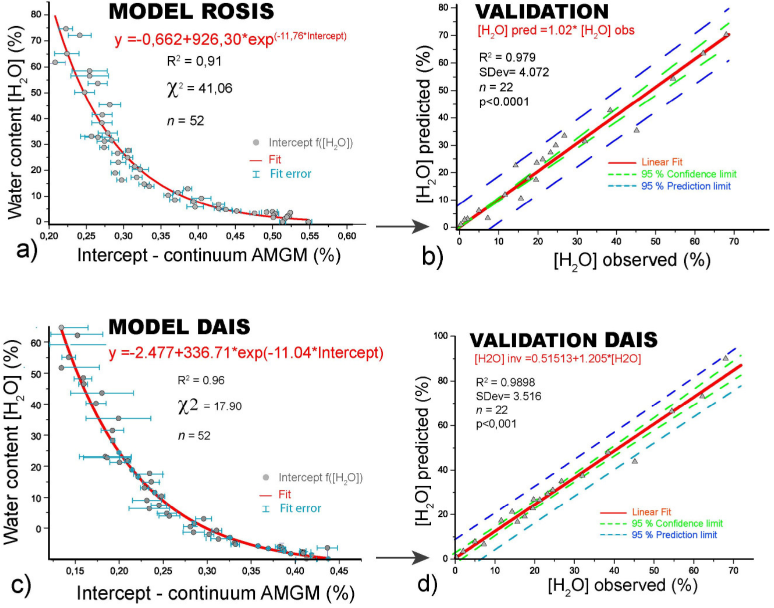


Figure 3. a) Exponential model to estimate water content after AMGM processed to ROSIS and DAIS spectral resolution. X-axis is the measured water content in the sample, Y-axis is the estimation of the continuum (intercept) for a sand sediment sample. b) Comparison between water content measured in the sample and water derived from predicted mode, inverting the equations derived from the training data set

3.2.3. Application to ROSIS and DAIS data

Models were applied to the DAIS and ROSIS images to derive maps of hydration state and then quantify the impact of sediment heterogeneities from moisture content variations. Figure 4 presents maps of water content derived from DAIS and ROSIS (strength at 0.97 µm – a; intercept continuum – b and c) over mudflats. Both techniques (absorption strength and continuum intercept) give satisfactory results when applied to ROSIS data (see r^2 on Figure 2). 0.97 µm water absorption strength seems to be more accurate than continuum intercept for DAIS data (see r^2 on Figure 3). Inversion of the resulting models on the images appear qualitatively correct, but ROSIS continuum analysis map shows underestimation of H_2O content when compared to DAIS Gaussian analysis map. We can also notice that the terrains where the higher water content is found cover larger areas than those with low water content. This can be explained by the fact that hydration form is influenced by the different sediment types. Areas which present saturated water are dominated by muddy-sandy to muddy sediments. Whereas, areas which present free water are dominated by sandy-muddy to sandy sediments. For image spectra, the general shape of the spectra and albedo are also influenced by other parameters, physical (particle size; surface roughness) and bio-chemical constituents (organic matter and minerals). Therefore, an independent way to derive particle size from remote sensing data appears necessary to address effects of particle sizes where heterogeneity in natural surfaces is present.

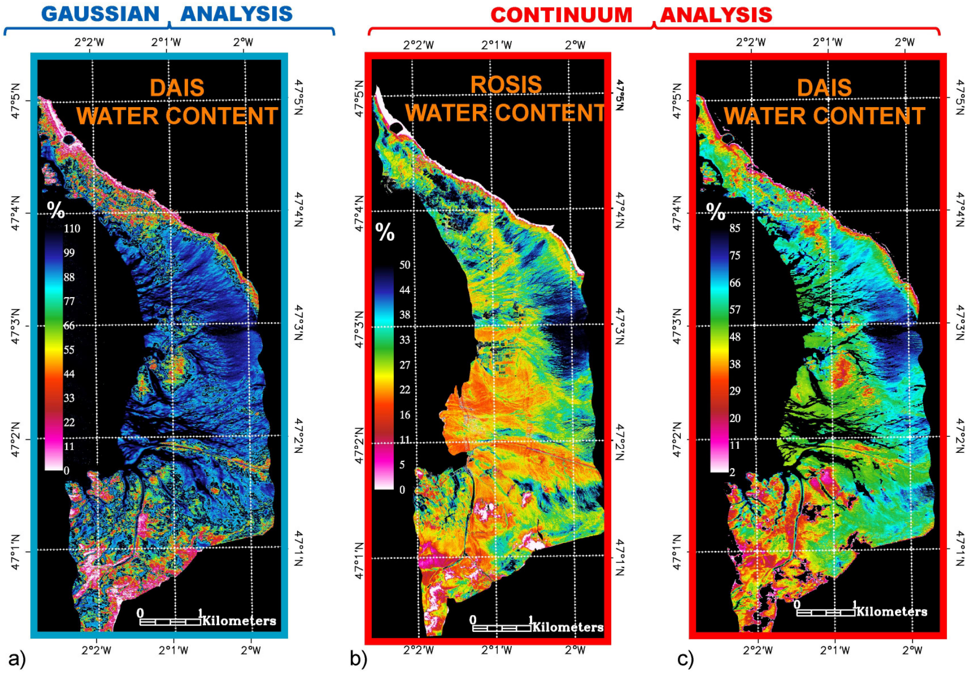
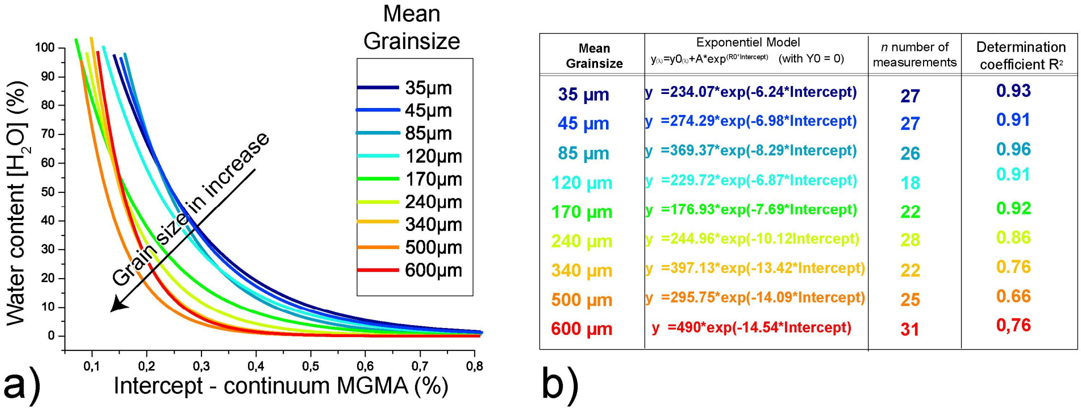


Figure 4. Map of surface water content as derived from regression equations applied to DAIS and ROSIS data**.** Saturated water was masked a) absorption strength at 0.97 μm; b) and c) continuum intercept

3.3 Grain-size, continuum, spectral contrast and moisture levels



Mean Grainsize	Exponentiel Model $y_{(\lambda)}=y0_{(\lambda)}+A*\exp^{(R0*\text{Intercept})}$ (with Y0 = 0)	*n* number of measurements	Determination coefficient R^2
35 μm	y =234.07*exp(-6.24*Intercept)	27	0.93
45 μm	y =274.29*exp(-6.98*Intercept)	27	0.91
85 μm	y =369.37*exp(-8.29*Intercept)	26	0.96
120 μm	y =229.72*exp(-6.87*Intercept)	18	0.91
170 μm	y =176.93*exp(-7.69*Intercept)	22	0.92
240 μm	y =244.96*exp(-10.12Intercept)	28	0.86
340 μm	y =397.13*exp(-13.42*Intercept)	22	0.76
500 μm	y =295.75*exp(-14.09*Intercept)	25	0.66
600 μm	y =490*exp(-14.54*Intercept)	31	0,76

Figure 5. a) Exponential model to estimate water content after AMGM processed to DAIS spectral resolution. X-axis is the measured water content in the sample, Y-axis is the intercept of the continuum for a sandy sediment sample. b) Table of exponential models for each fraction size *n* = number of measurements used in the regression and R^2 = determination coefficient

The goal of this section is to understand the relationship between particle size and continuum parameters. We examine the effects of particle size on the AMGM model using nine mean size fractions of beach sand. We will describe how particle sizes of sediment surfaces influence the estimation of water content. Continuum parameter (*i.e.* intercept) was calculated for nine (<35, 45; 85; 120; 170; 240; 340; 500; 600) mean size fractions of sand, for a known water content. We observe that, for similar water content, an increase in particle size corresponds to a decrease in the intercept of the continuum (Figure 5-a). This can be attributed to difference in granulometric properties: each sediment sample has a different sediment structure and porosity, and the particle size affects the reflectance, as predicted by the scattering theory. Albedo decreases with particle size. The intercept increases exponentially with water content for all size fractions (Figure 5-a-b). The table shows good r^2 between measured and predicted sediment moisture content (r^2: 0.66-0.96).

4. CONCLUSION

These results are based on physical and mathematical models and demonstrate the ability of AMGM to retrieve qualitative and quantitative information on sediment properties. We have demonstrated that water content can be estimated through specific water absorption band overtones with Gaussians function as well as the AMGM continuum. In this study, we present new results regarding the effects of grain size variations and moisture content for sandy materials on the 0.97 µm water absorption band. The strong exponential correlation between strength at 0.97 µm and the continuum intercept is the most promising spectral criteria to separate the effects of water content. This behaviour appears highly dependent on the sediment particle size. However, to be useful, this correlation should be reproducible for other hydrated sediment samples (sandy-mud, muddy-sand, mud, etc.).

In nature, sediment parameters are, from an environmental point of view, closely inter-related. The water content of sediments is highly correlated to sediment grain size and topography. It is important to separate the contribution of particle size and H_2O on continuum and absorption parameters. We have inverted experimental functions on the DAIS and ROSIS images to produce water content that appeared qualitatively correct. The algorithm is consistent and allows us to generate time-series for monitoring. This method can be applied to other geographic areas. However, laboratory measurements should be validated and calibrated in order to be applicable to other intertidal areas.

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